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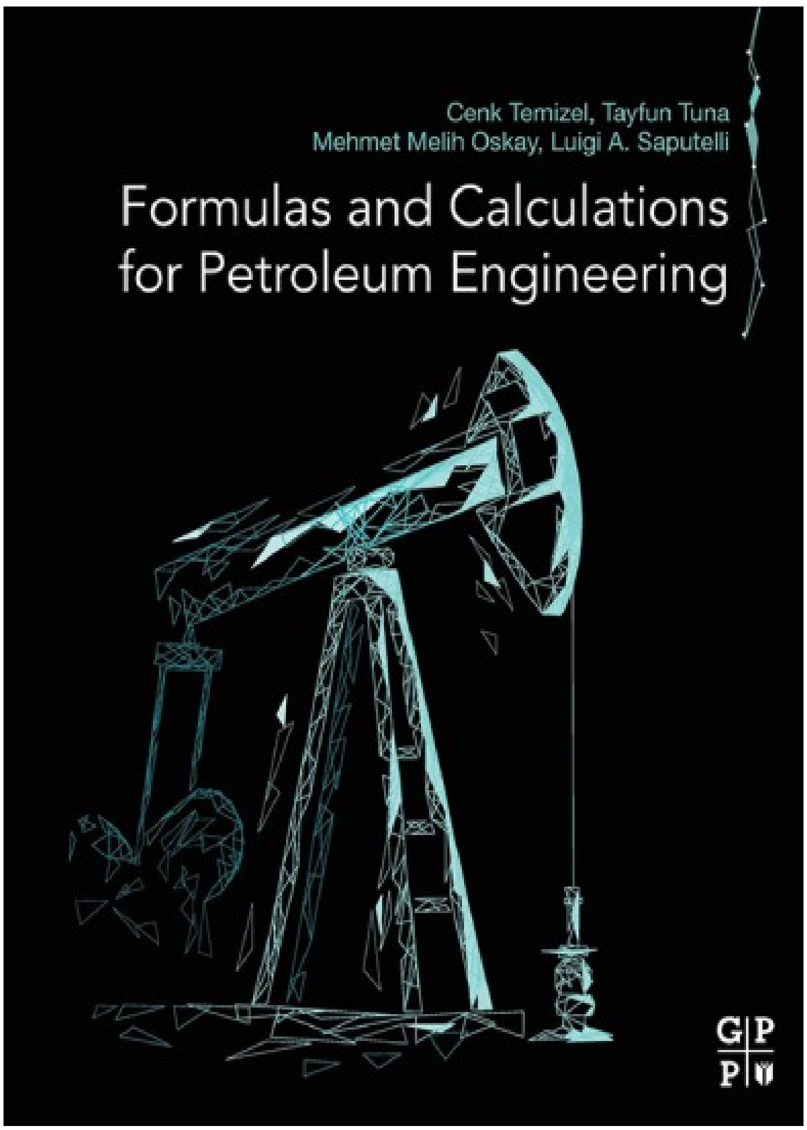

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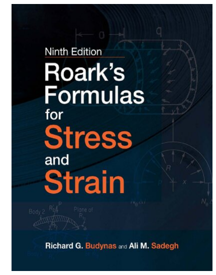

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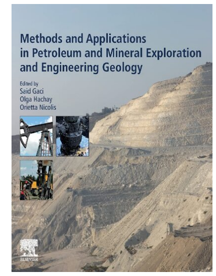

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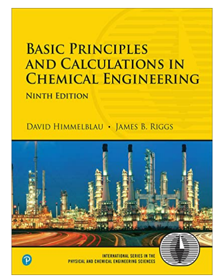

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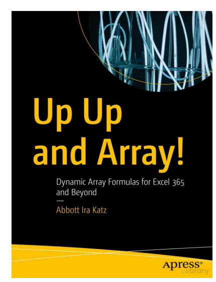

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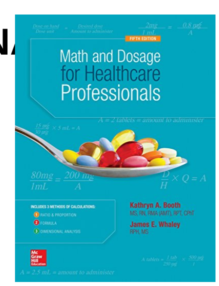

Cenk Temizel, Tayfun Tuna
Mehmet Melih Oskay, Luigi A. Saputelli

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Gulf Professional Publishing
An imprint of Elsevier

Gulf Professional Publishing is an imprint of Elsevier
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, United Kingdom

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-0-12-816508-9

For information on all Gulf Professional publications
visit our website at https://www.elsevier.com/books-and-journals

Publisher: Brian Romer
Senior Acquisition Editor: Katie Hammon
Editorial Project Manager: Ali Afzal-Khan
Production Project Manager: Sujatha Thirugnana Sambandam
Cover Designer: Christian Bilbow

Typeset by SPi Global, India

Biographies of authors

Cenk Temizel is a reservoir engineer with 15 years of international experience in the industry with expertise in reservoir simulation, smart fields, heavy oil, optimization, unconventionals and enhanced oil recovery. He was a teaching/research assistant at the University of Southern California and Stanford University before joining the industry. He won the 2nd place at SPE Global R&D Competition at SPE ATCE 2014 in Amsterdam and the 2nd place in Technical Excellence Awards at 22nd World Petroleum Congress in 2017 in Istanbul. He received the Halliburton Award in Innovation in 2012. He serves as a technical reviewer for petroleum engineering journals. His interests include reaction kinetics/dynamics of fluid flow in porous media and enhanced oil recovery processes. He served as a session chair and member of organizing committees for several SPE conferences. He has published around 100 publications in the area of reservoir management, production optimization, enhanced oil recovery processes and smart fields along with US patents. He holds a BS degree (Honors) from Middle East Technical University—Ankara (2003) and an MS degree (2005) from University of Southern California (USC), Los Angeles, CA both in petroleum engineering.

Tayfun Tuna is a data scientist and software developer who holds a MS and a PhD degree in computer science from the University of Houston. His graduate research focus was on text mining; applying machine learning techniques to lecture videos in order to segment video content for a better learning experience. He is a cofounder of Videopoints LLC, previously known as ICS Video Project, an interactive educational video platform which have been used more than 50K users across multiple university campuses. While he was the chief operating officer and principal investigator, his project is rewarded by National Science Foundation Small Business Innovation Research (NSF SBIR) Phase I Grant.

In his professional career, he has worked with Halliburton to develop a patented machine learning-based web-based interface that predicts chance of getting of stuck while drilling for oil. He has two patents and 20 research paper publications on educational technology, social networks, and oil&gas field.

Mehmet Melih Oskay earned his PhD from UT Austin, and he has been in academia and industry as advisors and managerial positions for more than 30 years at several major operators.

He has represented operators at Joint Operations Committee and Joint Operations Tender Committees.

He has taught at University of Texas—Austin, TX; Louisiana Tech University-Ruston, Louisiana; Middle East Technical University—Ankara, Turkey; and King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.

He has participated in several Organizing Committees and Session Chairmanship positions at many SPE Oil Show and Technical Conferences.

Luigi A. Saputelli is a reservoir engineering senior advisor with over 28 years of experience. He worked in various operators and services companies around the world. He is a founding member of the Society of Petroleum Engineers' Real-time Optimization Technical Interest Group and the Petroleum Data-driven Analytics technical section. He is the recipient of the 2015 SPE International Production and Operations Award.

He has published more than 90 industry papers on applied technologies related to reservoir management, real-time optimization, and production operations. He holds a BSc. in electronic engineer from Universidad Simon Bolivar (1990), with a master in petroleum engineering from Imperial College (1996), and a PhD in chemical engineering from University of Houston (2003). He also serves as managing partner for, a petroleum engineering services firm based in Houston.

Foreword

Formulas and Calculations for Petroleum Engineering unlocks the capability for any petroleum engineering individual, experienced or not, to solve problems and locate quick answers, eliminating nonproductive time spent searching for that right calculation. Enhanced with lab data experiments, practice examples, and a complimentary online software toolbox, the book presents the most convenient and practical reference for all oil and gas phases of a given project. Covering the full spectrum, this reference gives single-point reference to all critical modules, including drilling, production, reservoir engineering, well testing, well logging, enhanced oil recovery, well completion, fracturing, fluid flow, and even petroleum economics.

ptlbx.com *provides access to calculations of these formulas.*

Acknowledgement

Authors

This book is dedicated to my wife, my love, Saule who has supported me unconditionally in my endeavors and has been an inspiration for me in life with her love, care, and understanding and to my daughter Ada Ayca who has brought joy and happiness to our life and to my parents Yuksel and Rasim Temizel and my brother Efe for their continuous support and love.

Cenk Temizel

I am indebted to my wife Suhendan and to my daughter Ceyda for their unflagging support to finish this book.

Mehmet Melih Oskay

I dedicate this book to my parents Julia and Emilio, who are eternal symbols of unconditional love and true parenthood, from whom I learned what exemplary human values.

Luigi A. Saputelli

Reviewers

My effort that went into the completion of this book is dedicated to my wife Ezgi who assisted me with her love and patience, to Serkan who made me feel lucky to have an honest brother like him, and also to my beloved parents Fusun and Kaya Canbaz who gave their true love without any expectations and supported me with patience in any circumstances.

Celal Hakan Canbaz

I would like to express my deepest love and respect to especially my beloved parents and wife Elif who always has supported and inspired me to contribute to this book and my self-improvement in terms of both professional and personal ways during all my life.

Yildiray Palabiyik

Chapter 1

Reservoir engineering formulas and calculations

Chapter Outline

Formulas and Calculations for Petroleum Engineering. https://doi.org/10.1016/B978-0-12-816508-9.00001-9

1.1 API gravity

Input(s)

SG_o: Specific Gravity of Oil Phase (fraction)

Output(s)

API: API Gravity (dimensionless)

Formula(s)

$$API = \frac{141.5}{SG_o} - 131.5$$

Notes: $SG_o = \frac{\rho_{oil}}{\rho_{water}}$ at 60 F.

Reference: *Wikipedia.org*.

1.2 Average permeability for linear flow—Layered beds

Input(s)

k_1: Permeability for Layer 1 (mD)
k_2: Permeability for Layer 2 (mD)
k_3: Permeability for Layer 3 (mD)
A_1: Area of Layer 1 (ft^2)
A_2: Area of Layer 2 (ft^2)
A_3: Area of Layer 3 (ft^2)

Output(s)

k_{avg}: Average Permeability in Linear Systems when there is no crossflow between layers (mD)

Formula(s)

$$k_{avg} = \frac{k_1 * A_1 + k_2 * A_2 + k_3 * A_3}{A_1 + A_2 + A_3}$$

Reference: *Ahmed, T. (2006). Reservoir Engineering Handbook. Elsevier, Page: 238.*

1.3 Average permeability for linear flow—Series beds

Input(s)

k_1: Permeability for layer 1 (mD)
k_2: Permeability for layer 2 (mD)
k_3: Permeability for layer 3 (mD)
L_1: Length of layer 1 (ft)
L_2: Length of layer 2 (ft)
L_3: Length of layer 3 (ft)

Output(s)

k_{avg}: Average Permeability in Linear Systems Series (mD)

Formula(s)

$$k_{avg} = \frac{L_1 + L_2 + L_3}{\frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{L_3}{k_3}}$$

Reference: *Ahmed, T. (2006). Reservoir Engineering Handbook. Elsevier, Page: 240.*

1.4 Average permeability for parallel-layered systems

Input(s)

k_1: Permeability for Layer 1 (mD)
k_2: Permeability for Layer 2 (mD)
k_3: Permeability for Layer 3 (mD)
h_1: Height of Layer 1 (ft)
h_2: Height of Layer 2 (ft)
h_3: Height of Layer 3 (ft)

Output(s)

k_{avg}: Average Permeability for Parallel-layered Systems (mD)

Formula(s)

$$k_{avg} = \frac{k_1 * h_1 + k_2 * h_2 + k_3 * h_3}{h_1 + h_2 + h_3}$$

Reference: *Ahmed, T. (2006). Reservoir Engineering Handbook. Elsevier, Page: 237.*

1.5 Average permeability in radial systems

Input(s)

k_a: Permeability between r_w and r_a (mD)
k_e: Permeability between r_e and r_a (mD)
r_e: Drainage radius (ft)
r_w: Well bore radius (ft)
r_a: Radius lesser than r_e (ft)

Output(s)

k_{avg}: Average Permeability in Radial Systems Series (mD)

Formula(s)

$$k_{avg}=\frac{k_a * k_e * \ln\left(\frac{r_e}{r_w}\right)}{k_a * \ln\left(\frac{r_e}{r_a}\right)+k_e * \ln\left(\frac{r_a}{r_w}\right)}$$

Reference: *Applied Reservoir Engineering Vol. 1, Smith, Tracy & Farrar, Equation 7–7.*

1.6 Average temperature of a gas column

Input(s)

T_t: Tubing Head Temperature (°R)
T_b: Wellbore Temperature (°R)

Output(s)

T: Arithmetic Average Temperature (°R)

Formula(s)

$$T=\frac{T_t+T_b}{2}$$

Reference: *Ahmed, T., McKinney, P.D.2005. Advanced Reservoir Engineering, Gulf Publishing of Elsevier, Chapter: 3, Page: 199.*

1.7 Calculation of fractional flow curve

Input(s)

μ_w: Water Viscosity (cP)
k_{rw}: Relative Permeability to Water (dimensionless)
k_{ro}: Relative Permeability to Oil (dimensionless)
μ_o: Oil Viscosity (cP)

Output(s)

f_w: Fraction of Total Flowing Stream Composed of Water (dimensionless)

Formula(s)

$$f_w=\frac{1}{1+\frac{\mu_w * k_{ro}}{k_{rw} * \mu_o}}$$

Reference: *Craig Jr. F. F., 2004, the Reservoir Engineering Aspects of Waterflooding, Vol. 3. Richardson, Texas: Monograph Series, SPE, Page: 112.*

1.8 Capillary number

Input(s)

μ_w: Viscosity of Displacing Fluid (cP)
V: Characteristic Velocity (ft/D)
σ_{ow}: Surface or Interfacial Tension of Oil and Water Phases (dyn/cm)

Output(s)

N_c: Capillary Number (dimensionless)

Formula(s)

$$Nc = \frac{\mu_w * V}{\sigma_{ow}}$$

Reference: *Wikipedia.org*.

1.9 Capillary pressure

Input(s)

σ: Fluid interfacial Tension (dyn/cm)
θ: Angle of Wettability (degree)
r: Radius of Capillary (cm)

Output(s)

P_C: Capillary Pressure (dyn/cm)

Formula(s)

$$P_C = \frac{2 * \sigma * \cos(\theta)}{r}$$

Reference: *Wikipedia.org*.

1.10 Characteristic time for linear diffusion in reservoirs

Input(s)

Φ: Porosity (fraction)
β_f: Fluid Compressibility (1/psi)
β_r: Rock Compressibility (1/psi)
μ: Viscosity (cP)
l: Characteristic Length Scale of Diffusion (ft)
k: Permeability (mD)

Output(s)

τ: Time (s)

Formula(s)

$$\tau = \frac{\left(\Phi * \beta_f + \beta_r\right) * \mu * I^2}{k}$$

Reference: *Zoback, M. D. Reservoir Geomechanics, Cambridge University Express, UK, Page: 41.*

1.11 Cole plot

Input(s)

G: GIP (MSCF)
E_g: Gas Expansion Term (bbl/MSCF)
W_e: Water influx (bbl)

Output(s)

F: Underground Water Withdrawal (bbl)

Formula(s)

$$F = G * E_g + W_e$$

Reference: *Ahmed, T., McKinney, P. D. Advanced Reservoir Engineering, Gulf Publishing House, Burlington, MA, 2015.*

1.12 Communication between compartments in tight gas reservoirs

Input(s)

G: Gas in Place (MSCF)
E_g: Gas Expansion Term (bbl/MSCF)
W_e: Cumulative Water Influx (bbl)

Output(s)

F: Underground Fluid Withdrawal (bbl)

Formula(s)

$$F = G * E_g + W_e$$

Reference: *Ahmed, T., McKinney, P.D. 2005. Advanced Reservoir Engineering, Gulf Publishing of Elsevier, Chapter: 3, Page: 209.*

1.13 Communication factor in a compartment in tight gas reservoirs

Input(s)

K: Permeability (mD)
A: Area (ft^2)
T: Temperature (R)
L: Length of Compartment (ft)

Output(s)

C: Communication Factor (SCF/d/psi^2/cP)

Formula(s)

$$C = \frac{0.111924 * k * A}{T * L}$$

Reference: *Ahmed, T., McKinney, P.D. 2005. Advanced Reservoir Engineering, Gulf Publishing of Elsevier, Chapter: 3, Page: 235.*

1.14 Compressibility drive in gas reservoirs

Input(s)

G: Gas in place (MSCF)
G_P: Gas Produced (MSCF)
B_g: Gas Formation Volume Factor (MSCF/ft^3)
E_f: Gas Compressibility Drive (ft^3/MSCF)

Output(s)

CI: Compressibility Index (dimensionless)

Formula(s)

$$CI = \frac{G * E_f}{B_g * G_P}$$

Reference: *Ahmed, T. & McKinney, P. D. Advanced Reservoir Engineering, Gulf Publishing House, Burlington, MA, 2015.*

1.15 Correction factor—Hammerlindl

Input(s)

G: Gas in Place (MSCF)
G_p: Gas Produced (MSCF)
B_g: Gas Formation Volume Factor (bbl/MSCF)
$E_{f,\,w}$: Rock and Water Expansion Term (bbl/MSCF)

Output(s)

CDI: Compressibility Drive Index (dimensionless)

Formula(s)

$$CDI = \frac{G * E_{f,w}}{G_p * B_g}$$

Reference: *Ahmed, T., McKinney, P.D. 2005. Advanced Reservoir Engineering, Gulf Publishing of Elsevier, Chapter: 3, Page: 211.*

1.16 Critical rate for horizontal Wells in edge-water drive reservoirs

Input(s)

$e1$: Constant for C1 Equals +0.023 or − 0.023 (dimensionless)
$e2$: Constant for C2 equals +0.0013 or − 0.0013 (dimensionless)
$e3$: Constant for C3 equals +0.022 or − 0.022 (dimensionless)
$e4$: Constant for C4 equals +0.0013 or − 0.0013 (dimensionless)
Δ_ρ: Density Difference between water and oil or, oil and gas (gm/cc)

h: Pay Zone Thickness (ft)
L: Length of Well (ft)
x_e: Distance between Horizontal Well and Constant Pressure Boundary (ft)
μ_o: Oil Viscosity (cP)
k_h: Vertical Permeability (mD)
k_v: Horizontal Permeability (mD)

Output(s)

c_1: Dimensionless Constant for calculation (dimensionless)
c_2: Dimensionless Constant for calculation (dimensionless)
c_3: Dimensionless Constant for calculation (dimensionless)
c_4: Dimensionless Constant for calculation (dimensionless)
q_c: Dimensionless Critical Rate per Unit length (STB/day/ft)
q_o: Critical Rate (STB/day)
z_c: Critical Height Representing the Difference between the Apex of the Gas/Water Crest from the Well Elevation (ft)

Formula(s)

$$c_1 = 1.4426 + e1$$

$$c_2 = -0.9439 + e2$$

$$c_3 = 0.4812 + e3$$

$$c_4 = -0.9534 + e4$$

$$q_c = c_1 * \left(\frac{x_e}{h * \left(\frac{k_h}{k_v} \right)^{0.5}} \right)^{c_2}$$

$$q_o = \left(4.888 * 10^{-4}\right) * \Delta_\rho * h * (k_h * k_v)^{0.5} * L * \frac{q_c}{\mu_o}$$

$$z_c = c_3 * h * \left(\frac{x_e}{h * \left(\frac{k_h}{k_v} \right)^{0.5}} \right)^{c_4}$$

Reference: *Joshi, S.D. 1991, Horizontal Well Technology. Tulsa, Oklahoma: PennWell Publishing Company. Chapter: 7, Page: 309, 310.*

1.17 Crossflow index

Input(s)

N_{pcf}: Oil Recovery from Layered System with Crossflow (STB)
N_{pncf}: Oil Recovery from Stratified System with No Crossflow (STB)
N_{pu}: Oil Recovery from Uniform System with Average Permeability (STB)

Output(s)

CI: Crossflow Index (dimensionless)

Formula(s)

$$CI = \frac{N_{pcf} - N_{pncf}}{N_{pu} - N_{pncf}}$$

Reference: *Willhite, G.P. 1986. Waterflooding, Vol. 3. Richardson, Texas: Textbook Series, SPE, Chapter: 2, Page: 166.*

1.18 Cumulative effective compressibility—Fetkovich

Input(s)

S_{wi}: Initial Water Saturation (fraction)
$\overline{c}_w$: Cumulative Total Water Compressibility (1/psi)
M: Dimensionless Volume Ratio (dimensionless)
$\overline{c}_f$: Total PV (Formation) Compressibility (psi^{-1})

Output(s)

$\overline{c}_e$: Effective Compressibility (1/psi)

Formula(s)

$$\overline{c}_e = \frac{S_{wi} * \overline{c}_w + M * \left(\overline{c}_f + \overline{c}_w\right) + \overline{c}_f}{1 - S_{wi}}$$

Reference: *Ahmed, T., McKinney, P.D. 2005. Advanced Reservoir Engineering, Gulf Publishing of Elsevier, Chapter: 3, Page: 215,216.*

1.19 Cumulative gas production—Tarner's method

Input(s)

N: Initial Oil-in Place (STB)
R_s: Gas Solubility (SCF/STB)
R_{si}: Initial Gas Solubility (SCF/STB)
B_o: Oil Formation Volume Factor at the Assumed Reservoir Pressure (bbl/STB)
B_{oi}: Oil Formation Volume Factor at Initial Reservoir Pressure (bbl/STB)
B_g: Gas Formation Volume Factor at the Assumed Reservoir Pressure (bbl/SCF)
N_p: Cumulative Oil Production (STB)

Output(s)

G_p: Cumulative Gas Production (SCF)

Formula(s)

$$G_p = N * \left[\left(R_{si} - R_s\right) - \left(\frac{B_{oi} - B_o}{B_g}\right)\right] - N_p * \left[\frac{B_o}{B_g} - R_s\right]$$

Reference: *Ahmed, T., McKinney, P.D. 2005. Advanced Reservoir Engineering, Gulf Publishing of Elsevier, Chapter: 5, Page: 340.*

1.20 Cumulative oil production—Undersaturated oil reservoirs

Input(s)

N: Initial Oil-in Place (STB)
c_e: Effective Compressibility (1/psi)
B_o: Oil Formation Volume Factor at the Assumed Reservoir Pressure (bbl/STB)
B_{oi}: Oil Formation Volume Factor at Initial Reservoir Pressure (bbl/STB)
ΔP: Pressure Differential (psi)

Output(s)

N_p: Cumulative Oil Production (STB)

Formula(s)

$$N_p = N * c_e * \left(\frac{B_o}{B_{oi}}\right) * \Delta P$$

Reference: *Ahmed, T., McKinney, P.D. 2005. Advanced Reservoir Engineering, Gulf Publishing of Elsevier, Chapter: 5, Page: 333.*

1.21 Deliverability equation for shallow gas reservoirs

Input(s)

k: Permeability (mD)
h: Thickness (ft)
T: Temperature (°R)
μ: Viscosity (cP)
z: Compressibility Factor (dimensionless)
r_e: Radius of Drainage Area (ft)
r_w: Wellbore Radius (ft)

Output(s)

C: Performance Coefficient (dimensionless)

Formula(s)

$$C = \frac{k * h}{1422 * T * \mu_g * Z * \left(\ln\left(\frac{r_e}{r_w}\right) - 0.5 \right)}$$

Reference: *Ahmed, T., McKinney, P.D. 2005. Advanced Reservoir Engineering, Gulf Publishing of Elsevier, Chapter: 3, Page: 287.*

1.22 Dimensionless pressure—Kamal and Brigham

Input(s)

Q: Flow Rate (STB/day)
$\bar{k}$: Average Permeability (mD)
h: Thickness (ft)

B: Formation Volume Factor (bbl/STB)
μ: Viscosity (cP)
ΔP: Pressure Difference (psi)

Output(s)

ΔP_d: Dimensionless Pressure (dimensionless)

Formula(s)

$$\Delta P_d = \frac{\bar{k} * h * \Delta P}{141.2 * Q * \mu * B}$$

Reference: *Ahmed, T., McKinney, P.D. 2005. Advanced Reservoir Engineering, Gulf Publishing of Elsevier, Chapter: 1, Page: 125.*

1.23 Dimensionless radius of radial flow—Constant-rate production

Input(s)

r: Effective Radius/Reservoir Radius (ft)
r_w: Wellbore Radius (ft)

Output(s)

r_d: Dimensionless Radius (dimensionless)

Formula(s)

$$r_d = \frac{r}{r_w}$$

Reference: *Lee, J., Rollins, J. B., & Spivey, J. P. (2003). Pressure Transient Testing (Vol. 9). Richardson, Texas: Society of Petroleum Engineers, Page: 8.*

1.24 Dimensionless time—Myhill and Stegemeier's method

Input(s)

M_s: Volumetric Heat Capacity of Steam (btu/ft^3 K)
M_R: Volumetric Heat Capacity of the Reservoir (btu/ft^3 K)
α_s: Overburden Heat Transfer Coefficient (ft^2/d)
h_t: Thickness of Column (ft)
t: Time (day)

Output(s)

t_D: Dimensionless Time (dimensionless)

Formula(s)

$$t_D = 4 * \left(\frac{M_s}{M_R}\right)^2 * \left(\frac{\alpha_s}{h_t^2}\right) * t$$

Reference: *Prats, M. 1986. Thermal Recovery. Society of Petroleum Engineers, New York, Chapter: 5, Page: 44.*

1.25 Dimensionless time for interference testing in homogeneous reservoirs—Earlougher

Input(s)

k: Permeability (mD)
ø: Porosity (fraction)
t: Time (h)
k: Overall Production (mD)
μ: Viscosity (cP)
c_t: Total Compressibility (1/psi)
r_w: Wellbore Radius (ft)

Output(s)

t_D: Dimensionless Time (dimensionless)

Formula(s)

$$t_D = \frac{0.0002637 * k * t}{ø * c_t * \mu * \left(r_w^2\right)}$$

Reference: *Ahmed, T., McKinney, P.D. 2005. Advanced Reservoir Engineering, Gulf Publishing of Elsevier, Chapter: 1, Page: 117.*

1.26 Dimensionless vertical well critical rate correlations—Hoyland, Papatzacos, and Skjaeveland

Input(s)

h: Oil Column Thickness (ft)
k_h: Effective Oil Permeability (mD)
ρ_w: Water Density (g/cc)
μ_o: Oil Viscosity (cP)
ρ_o: Oil Density (g/cc)
B_o: Oil Formation Volume Factor (RB/STB)
q_o: Critical Oil Rate (STB/day)

Output(s)

Q_{oD}: Dimensionless Critical Rate (dimensionless)

Formula(s)

$$QoD = 651.4 * \mu_o * B_o * \frac{q_o}{h^2 * (\rho_w - \rho_o) * k_h}$$

Reference: *Reservoir Engineering Handbook, Fourth Edition, Ahmed, Page: 607.*

1.27 Dimensionless wellbore storage coefficient of radial flow—Constant-rate production

Input(s)

h: Reservoir Thickness (ft)
C: Wellbore Storage Coefficient (STB/psi)

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